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Raghav Sharma, P. Dürrenfeld, E. Iacocca, O. G. Heinonen, J. Åkerman, and P. K. Muduli

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Mode-hopping mechanism generating colored noise in a magnetic tunnel junction based spin torque oscillator

Raghav Sharma,[1] P. Dürrenfeld,[2] E. Iacocca,[2] O. G. Heinonen,[3] J. Åkerman,[2,4] and P. K. Muduli[1,2]
[1]*Department of Physics, Indian Institute of Technology, Delhi, New Delhi 110016, India*
[2]*Department of Physics, University of Gothenburg, Gothenburg 412 96, Sweden*
[3]*Argonne National Laboratory, Materials Science Division, Lemont, Illinois 60439, USA*
[4]*Materials Physics, School of ICT, KTH-Royal Institute of Technology, Electrum 229, Kista 164 40, Sweden*

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The frequency noise spectrum of a magnetic tunnel junction based spin torque oscillator is examined where multiple modes and mode-hopping events are observed. The frequency noise spectrum is found to consist of both white noise and 1/*f* frequency noise. We find a systematic and similar dependence of both white noise and 1/*f* frequency noise on bias current and the relative angle between the reference and free layers, which changes the effective damping and hence the mode-hopping behavior in this system. The frequency at which the 1/*f* frequency noise changes to white noise increases as the free layer is aligned away from the anti-parallel orientation w.r.t the reference layer. These results indicate that the origin of 1/*f* frequency noise is related to mode-hopping, which produces both white noise as well as 1/f frequency noise similar to the case of ring lasers. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4896634]

Spin transfer torque allows manipulation of magnetization dynamics using spin polarized currents instead of magnetic fields.[1,2] The spin transfer torque can counteract the natural damping of the system and, above a threshold current, leads to the precession of the magnetization. The precession can be potentially used for applications in so-called spin torque oscillator (STO). Typically, a STO is composed of a fixed magnetic layer, a non-magnetic spacer, and a free magnetic layer. The magnetization of the free layer (FL) is excited into steady state oscillations, which can be detected as a high frequency voltage by virtue of either the giant magnetoresistance (GMR) or tunneling magnetoresistance (TMR) effects. STOs are becoming important for communication applications due to advantages such as large frequency tuning range,[3–5] high speed modulation,[6–8] submicron footprints,[9] and straightforward integration with semiconductor technology using the same processes as magnetoresistive random access memory.[10,11] However, the large linewidth of these oscillators is a limitation for applications. Minimizing this linewidth requires a detailed understanding of the underlying mechanisms. Existing theories of single mode STO consider purely white frequency noise that arises due to thermal phase noise.[12–17] However, recent experiments have shown the presence of an unexpected 1/*f* frequency noise in both GMR pseudo spin valves[18,19] and magnetic tunnel junction (MTJ)[20] based STOs. The 1/*f* frequency noise causes linewidth broadening as measurement time increases.[18] The origin of the 1/*f* frequency noise is yet to be explained. More recently, a theory of multi-mode STOs[21,22] was developed, motivated by several experiments showing mode-hopping[23] as well as mode-coexistence.[24] However, it is yet to be explored if such a multi-mode theory is able to explain the presence of 1/*f* frequency noise.

Here, we experimentally explore the possible origin of 1/*f* frequency noise in a system where mode-hopping can be systematically controlled by bias current and the angle of applied field. We perform simultaneous frequency and time-domain measurements to study frequency noise and its impact on spectrum analyzer linewidth as a function of bias current and the angle between the free and fixed layers. We show that the increase of white and 1/*f* frequency noise as the free layer is aligned away from the anti-parallel orientation w.r.t the reference layer (RL) is related to mode-hopping.

The MTJ based STOs[23,25] consist of IrMn (5)/CoFe (2.1)/Ru (0.81)/CoFe (1)/CoFeB (1.5)/MgO (1)/CoFeB (3.5) (thicknesses in nm), where the bottom CoFe layer is the pinned layer (PL), the composite CoFe/CoFeB represents the RL, and the top CoFeB layer is the FL. The device has a *circular* cross section with an approximate diameter of 240 nm, and a resistance-area product of 1.5 $\Omega\ \mu m^2$. The measured tunneling magnetoresistance of the investigated device is 75%. The RL magnetization equilibrium direction is taken to be $\varphi = 0^\circ$ of the applied field. We use the convention that a positive current corresponds to electrons flowing from the RL to the FL. The experimental setup is shown in Fig. 1(a). The signal generated from the device is first amplified using a low noise 1–18 GHz, 38 dB amplifier. The signal is then divided into two parts using a power divider. One part of the signal is measured using the spectrum analyzer (frequency domain), while the other part is measured using a digitizer (time-domain) after mixing down and further amplification (1 kHz–500 MHz, gain 33 dB). The local oscillator (LO) frequency is adjusted during each measurement to obtain a mixed down signal of 250 MHz. The digitizer samples the waveform at a sampling rate of 2 GS/s. Example measurements before and after mixing down are shown in Figs. 1(b) and 1(c), respectively. Figure 1(b) shows the spectrum analyzer measurement at $I = 7$ mA, $H = 400$ Oe, and $\varphi = 196^\circ$. A selected segment of the corresponding mixed down time trace is shown in Fig. 1(c). The total length of each time trace was 50 μs. The inset shows the fast Fourier transform

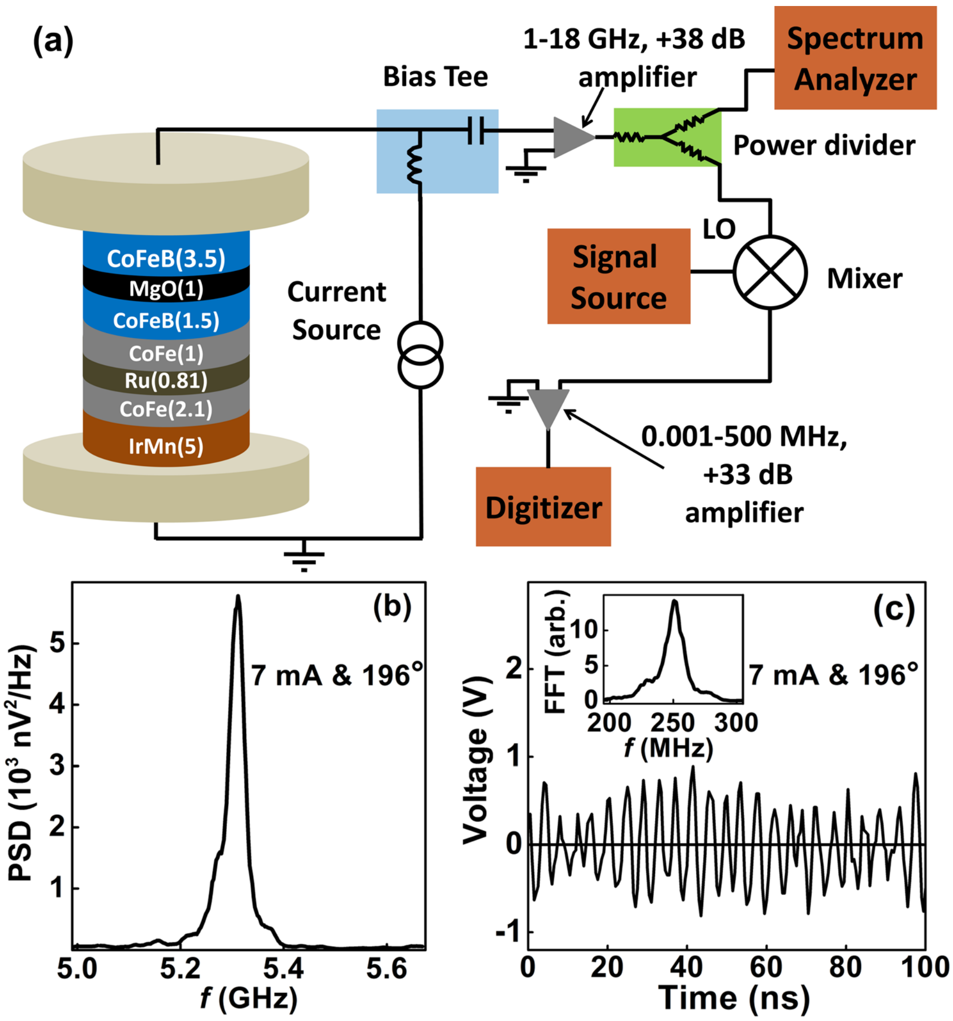

FIG. 1. (a) Schematic of the setup used for frequency noise measurement. (b) Example of spectra measured in spectrum analyzer at $I_{dc} = 7\,\text{mA}$ and $\varphi = 196°$. (c) The corresponding time trace measured in the digitizer. The inset shows FFT of the time trace.

(FFT) of the time trace confirming the frequency to be 250 MHz.

All measurements are done at a fixed magnetic field of $H = 400\,\text{Oe}$ by varying the in-plane field angle in the range $\varphi = 140° - 220°$, for which the free layer rotates coherently with the applied field. Hence, the applied field angle is equal to the angle between free and fixed layer.[5] The device shows multiple modes in frequency domain. The amplitudes of the modes vary with both current and the angle between the free and fixed layer.[23] The best signal is obtained at $\varphi = 196°$, which is near antiparallel alignment between the free and fixed layer. Frequency doubling limits the measured signal at $\varphi = 180°$, the exact antiparallel alignment between the free and fixed layer.[5] At $\varphi = 196°$, the threshold current is 6.5 mA though thermally excited signals can be observed already at a current of 1 mA. At $\varphi = 196°$ and $I = 7\,\text{mA}$ the measured signal [Fig. 1(b)] is primarily a single mode with linewidth of about 31 MHz. However, as many as five modes can be detected as the angle is varied in the range $\varphi = 140° - 220°$ at $I = 7\,\text{mA}$ [see Fig. 1(b) in Ref. 23]. We analyze the mixed down signal from the strongest mode, which is a bulk mode and corresponds to mode m_2 of Ref. 23.

In order to calculate frequency noise, we used the zero crossing method discussed in Ref. 18. First, a numerical bandpass filter was applied to the raw time trace to remove unwanted noise signals from the waveform due to oscilloscope, preamplifier noise, and other noise variations. We obtain qualitatively similar results for filter widths of 200 to 500 MHz. The presented results are for a filter width of 200 MHz around the mean frequency. Then, we calculate the power spectral density (PSD) of the phase deviation $S_\phi(f)$ using half-overlapping segments, each multiplied by a Hann window. Finally, the frequency noise $S_\nu(f)$ was obtained from the phase noise by using the relation $S_\phi(f) = f^2 S_\nu(f)$. Figure 2 shows a comparison between the frequency noise at $\varphi = 196°$ and $\varphi = 220°$ for (a) $I = 7\,\text{mA}$ and (b) $I = 3\,\text{mA}$, respectively. Here, $I = 3\,\text{mA}$ is below threshold (for both angles) and corresponds to the minimum current, at which the signal was above noise level in the digitizer. From Fig. 2, it is observed that the white noise is higher at the lowest current ($I = 3\,\text{mA}$) and the highest angle ($\varphi = 220°$). Detailed investigation at other currents and angles show that the frequency noise is a combination of white noise at higher frequencies and colored noise at lower frequencies, similar to previous studies.[18,20] White noise, S_{wh} is frequency independent whereas colored noise depends approximately on the inverse of the frequency (1/*f*). As pointed out previously, the case of $\varphi = 196°$ and $I = 7\,\text{mA}$ is close to single mode excitation. At this condition, the device exhibits lower white noise as well as 1/*f* frequency noise.

We determine the contribution of white noise, S_{wh} to the spectrum analyzer linewidth Δf, using $\Delta f_{wh} = \pi S_{wh}$.[18] Figure 3 shows a comparison between the linewidth calculated from the white noise, Δf_{wh}, and the measured spectrum analyzer

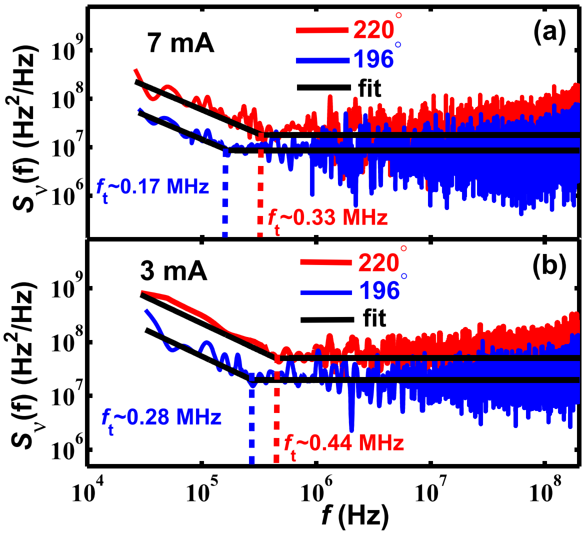

FIG. 2. Comparison of frequency noise at $\varphi = 196°$ and $\varphi = 220°$ for (a) $I = 7$ mA and (b) $I = 3$ mA. The black lines are fits as described in the main text.

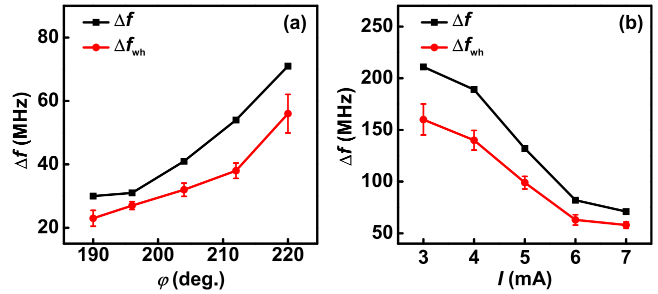

FIG. 3. Comparison of linewidth calculated from white noise with the measured spectrum analyzer linewidth (a) as a function of angle at $I = 7$ mA, and (b) as a function of current at $\varphi = 220°$.

linewidth, Δf, as a function of (a) angle at $I = 7$ mA and (b) current at $\varphi = 220°$. There is a qualitative agreement between Δf_{wh} and Δf. However, there is also a clear quantitative disagreement as Δf is larger than Δf_{wh}. In fact, $\Delta f / \Delta f_{wh}$ was found to be around 1.1–1.5. Thus, white noise alone is not able to fully account for the spectrum analyzer linewidth.

In order to determine the contribution of 1/*f* frequency noise to linewidth broadening, we first determine the time scale of 1/*f* frequency noise. We define the transformation frequency f_t, where the white noise transforms into the 1/*f* frequency noise. The angle and current dependence of f_t is shown in Fig. 4. The transformation frequency f_t is found to vary in the range of 140 kHz–500 kHz, indicating that 1/*f* frequency noise becomes significant at time scales larger than 2 μs, which is significantly lower than the spectrum analyzer measurement time scale (order of several seconds). This shows that the spectrum analyzer linewidth may include additional linewidth broadening due to 1/*f* frequency noise.

With varying the angle away from the antiparallel orientation, f_t increases or equivalently the extent of the 1/*f* frequency noise increases. Similarly with lowering current, f_t increases. We found a clear increase of the ratio $\Delta f / \Delta f_{wh}$ with f_t as shown in Fig. 4(c). The figure shows that the agreement between Δf and Δf_{wh} becomes worse with the increase of f_t or the 1/*f* frequency noise. In fact, the spectrum analyzer linewidth Δf is higher for higher 1/*f* frequency noise. In Ref. 18, Keller *et al.*, have reported that 1/*f* frequency noise increases spectrum analyzer linewidth Δf. However, no direct and systematic behavior of Δf with 1/*f* frequency noise was reported. In fact, their data did not show any systematic variation of 1/*f* frequency noise with bias current and magnetic field. The conclusion was based on an indirect measurement of Δf with measurement time. In our devices, we are able to systematically control 1/*f* frequency noise and show a direct proof that Δf is increased with 1/*f* frequency noise. We believe the behavior of f_t and hence 1/*f* frequency noise with angle and current is directly linked to a changing mode-hopping in the device. As the angle is increased, the rate of mode-hopping increases[23] [Fig. 4(a)], and hence, an increase in f_t is observed. Similarly at lower current, f_t is higher [Fig. 4(b)], since mode-hopping is also higher at currents below threshold.

Now we discuss possible origins of the 1/*f* frequency noise. Our results show that the 1/*f* frequency noise varies rather systematically with angle and current unlike Ref. 18. This implies that the origin of 1/*f* frequency noise is not related to the experimental setup components such as amplifiers and mixer. Since we see a significant variation of 1/*f* frequency noise in a single device by varying current and the angle between free and fixed layer, it is unlikely that 1/*f* frequency noise originates from specific device imperfections such as barrier quality or defects in the magnetic layer of the tunnel junction. Our results show that both white noise and 1/*f* frequency noise are higher at low current and high angle (i.e., away from antiparallel alignment between free and fixed layer). In a previous study,[23] we found a similar dependence of mode-hopping with angle and current. The mechanism for mode-hopping stems from an effective linear coupling between low-lying modes mediated by a thermal bath of magnons.[21–23] Since we observed a similar dependence of the 1/*f* frequency noise, we believe mode-hopping on a large time scale leads to the 1/*f* frequency noise in these

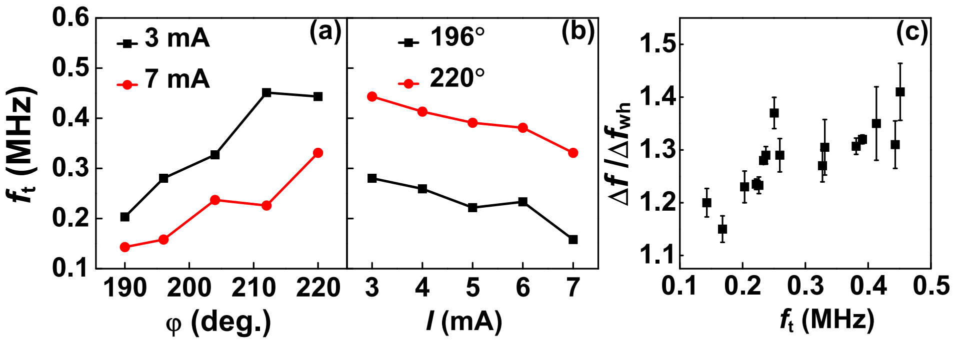

FIG. 4. (a) Transition frequency vs. angle at $I = 3$ mA and $I = 7$ mA; (b) Transition frequency vs. current at $\varphi = 196°$ and $\varphi = 220°$. (c) Plot of $\Delta f / \Delta f_{wh}$ vs. f_t.

devices. In fact, in the analytically similar case of ring lasers, noise arising from mode-hopping events was shown to have a 1/*f*-dependence when two external cavity modes are involved in the mode-hopping.[26] We believe there are two sources of 1/*f* frequency noise in STOs. One is intrinsic in the sense that it appears for single-mode STOs,[18] the origin of which is unclear. The second originates in the mode-hopping: each mode-hopping event leads to a random phase slip or jump in the phase of the oscillator.[21] These random phase jumps limit the phase correlation time to the order of the time τ_0 between mode hopping events. As the frequency is the rate of phase accumulation, based on general arguments by Kuzovlev and co-workers,[27] the limit on the phase correlation imposed by mode-hopping events will lead to a 1/*f* spectrum of the rate of phase accumulation, i.e., the frequency noise will have a 1/*f*-character. From this, it also follows immediately that the amplitude of the 1/*f* part of the frequency noise is approximately proportional to τ_0^{-1}—the more frequent the mode-hopping events are, the larger the amplitude of the frequency 1/*f*-noise.

The presence of 1/*f* frequency noise implies that the STO frequency becomes unpredictable for large time scales ($>2\mu$ s), making this noise undesirable for practical applications. Based on our results, we predict that 1/*f* frequency noise can be minimized at currents near threshold and for antiparallel orientation between the free and the reference layer, at which the natural damping is balanced by the spin torque leading to decreased mode-hopping.[23] As explained in Ref. 23, mode-hopping is also present for currents above threshold. Thus, our results indicate that the 1/*f* frequency noise will also be present for currents above threshold. However, the 1/*f* frequency noise has also been observed in nano-contact based STOs where no mode-hopping is expected since the excitation is primarily single mode.[18] A very recent study indicates that the 1/*f* frequency noise in nano-contact based STOs is related to the microstructural quality of the deposited films.[19] However, our results show that 1/*f* frequency noise in the MTJ-STOs is intrinsic to the device and is caused by mode-hopping events, which are understood as thermally activated.[21,22] Hence, single mode excitation and lower temperature can lead to a reduction of 1/*f* frequency noise in MTJ-STOs.

In summary, we reported on frequency noise in a MTJ-STO. The rate of mode-hopping was carefully controlled by varying the bias current and the angle between the free and the reference layer. This allowed us to study the influence of mode-hoping on frequency noise and in particular the 1/*f* frequency noise. The results indicate a direct correlation of 1/*f* frequency noise with mode-hopping. The results are important for the understating of 1/*f* frequency noise in STOs. We also discussed how 1/*f* frequency noise can be minimized in these devices for practical applications.

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